Interstellar medium and primordial black holes

Hyungjin Kim
Weizmann Institute of Science

A possible range of DM mass

extends over ~ O(10^90)

ULDM

BH

$10^{-22}\,\mathrm{eV}$

$10^{57}\,\mathrm{GeV}$

To maximize a discovery potential

we should utilize existing tools as much as possible

ULDM BH

$10^{-22}\,\mathrm{eV}$ — $10^{57}\,\mathrm{GeV}$

resonant cavities

NMR

Interferometry

atomic clocks

Colliders

Noble liquid detectors

Semiconductor devices

Astrophysical systems

And many others …

We will focus on

Interstellar medium (ISM)

and discuss its potential for DM searches with an example of

Primordial Black Holes

Interstellar medium is everything between stars

It includes gas, dust, and so on

PBH dark matter is a decaying dark matter

Particles from Hawking evaporation interact with **ISM**

and may heat the interstellar gas

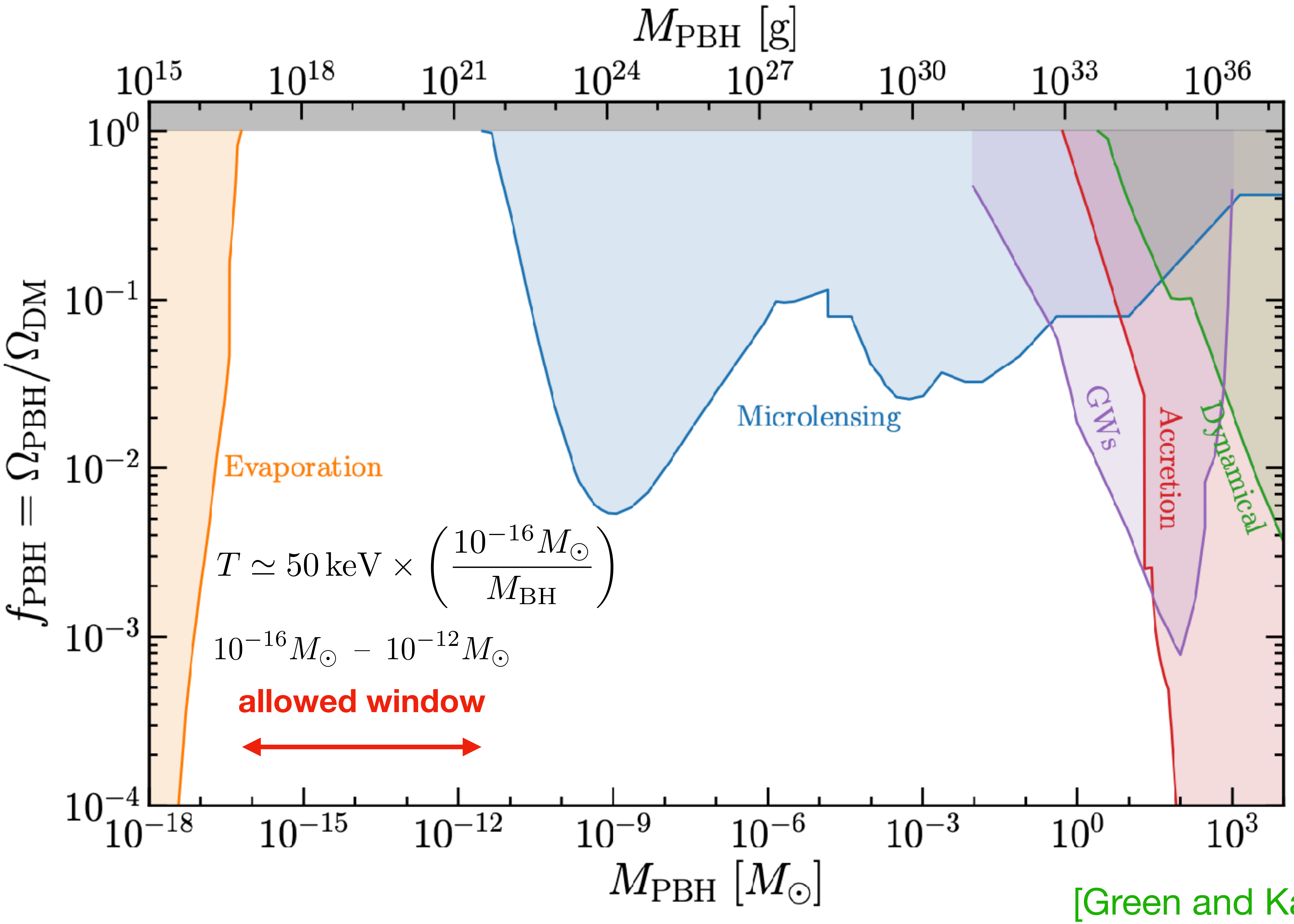
Can excessive heating be constrained by ISM temperature measurement ?

To see this we will consider

$$\frac{dE}{dtdV} = \mathcal{H} - \mathcal{C}$$

cooling rate

heating rate



[Green and Kavanagh 20]

What is ISM

and how does it cool / heat ?

Phase of interstellar medium

Component	T (K)	n (cm^{-3})
Molecular	10–20	10^2–10^6
Cold atomic	50–100	20–50
Warm atomic	6000–10 000	0.2–0.5
Warm ionized	~8000	0.2–0.5
Hot ionized	$\sim 10^6$	~0.0065

[Ferriere 01]

[Credit: ESO]

[Credit: NASA, ESA and the Hubble Heritage Team (STScI/AURA)]

[HI4PI Collaboration 16]

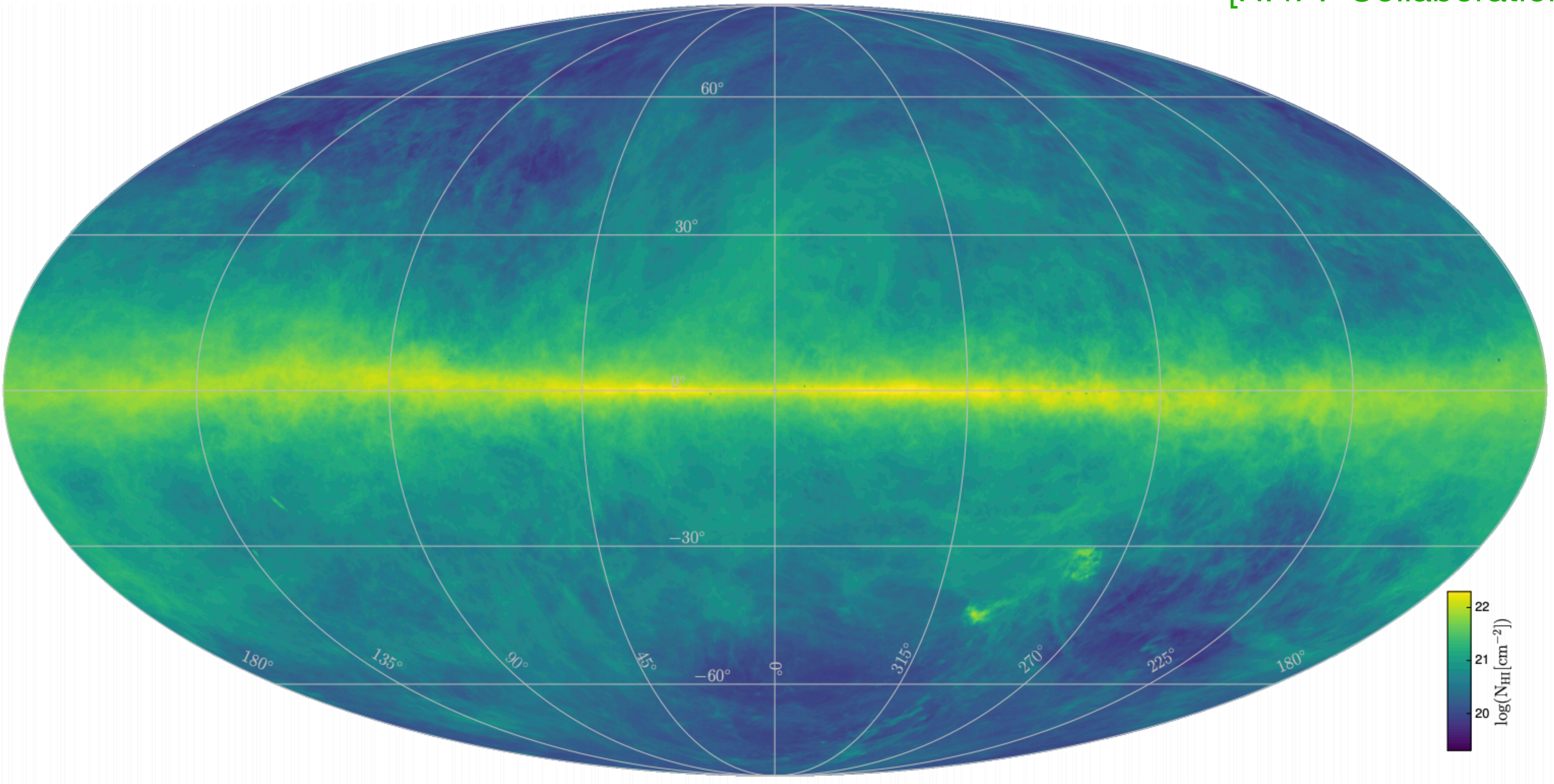


Fig. 2. HI4PI: all-sky column density map of H I gas from EBHIS and GASS data as integrated over the full velocity range $-600 \leq v_{\rm lsr} \leq 600\ {\rm km\,s^{-1}}$. The map is in Galactic coordinates using Mollweide projection.

We will be interested in

Warm Neutral Medium (WNM)

Component	T (K)	n (cm^{-3})
Molecular	10–20	10^2–10^6
Cold atomic	50–100	20–50
Warm atomic	6000–10 000	0.2–0.5
Warm ionized	~8000	0.2–0.5
Hot ionized	$\sim 10^6$	~0.0065

[Ferriere 01]

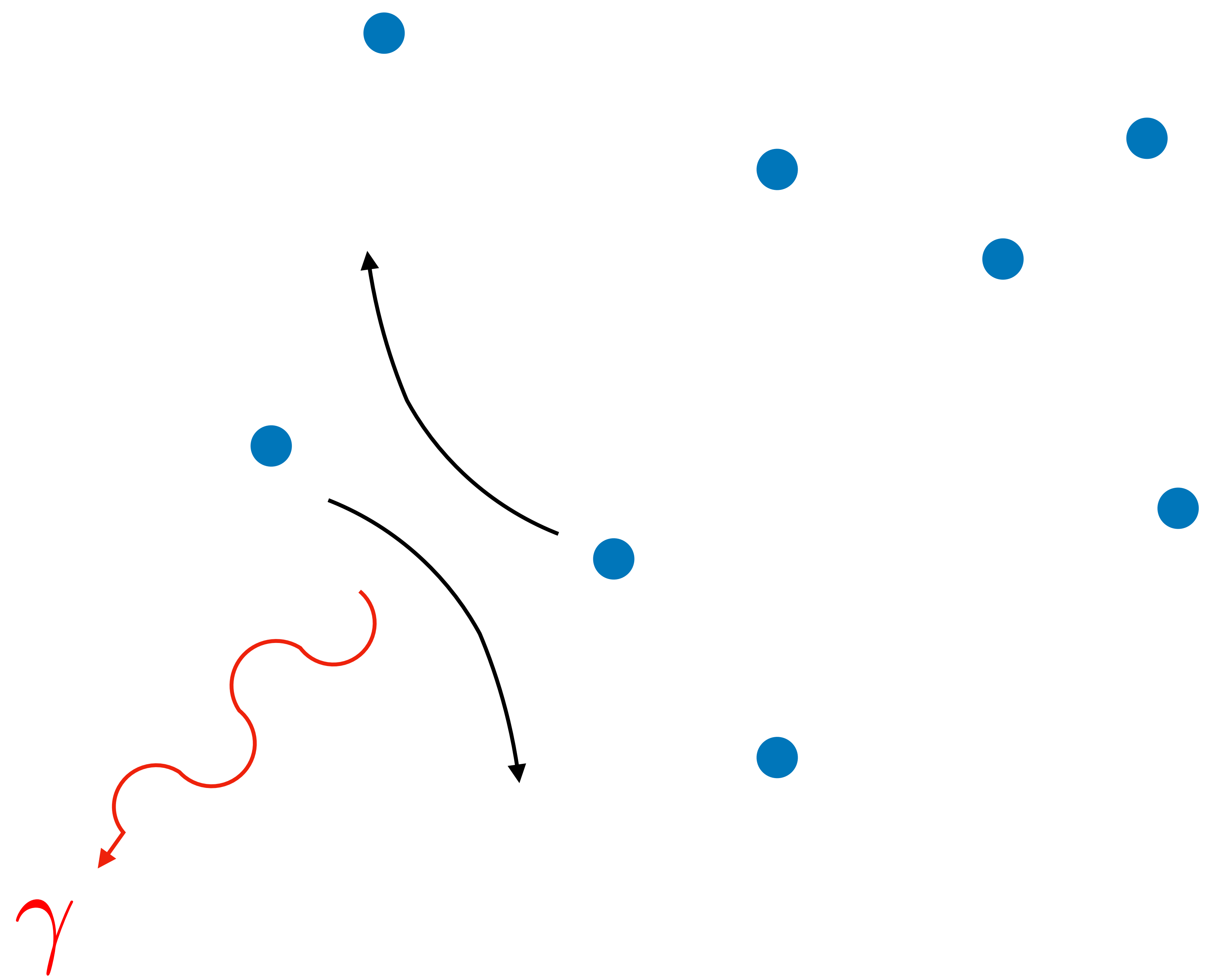
We are interested in computing the gas cooling rate

$$\frac{dE}{dt dV} = \mathcal{H} - \mathcal{C}$$

what contributes to it ?

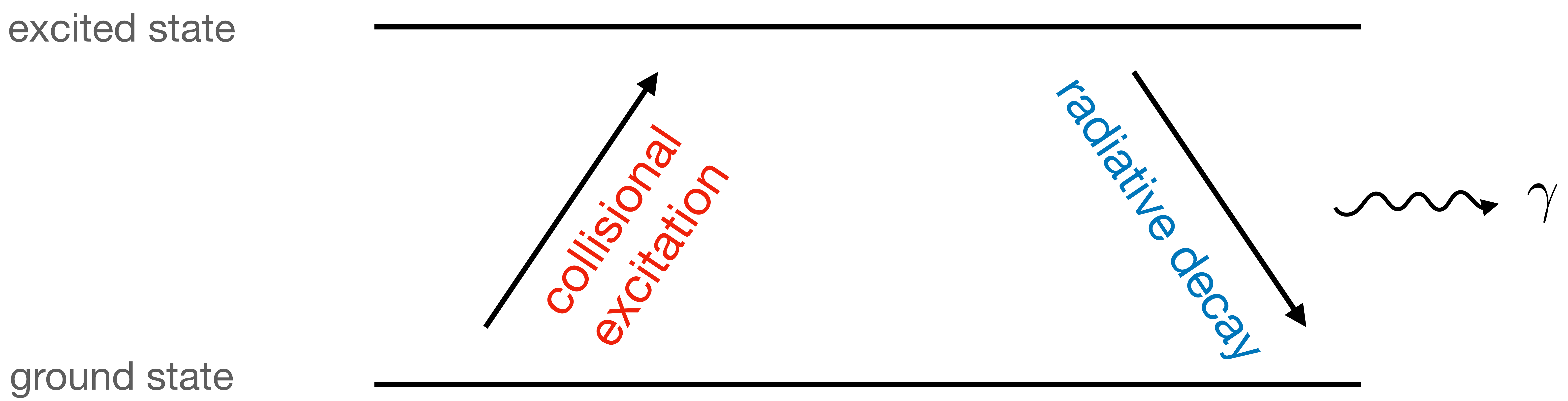
Cooling is a physical process that extracts energy

from the system to environment



it takes place through the emission of photons

Photon emission happens through line emission



collisional excitation converts kinetic energy into internal energy

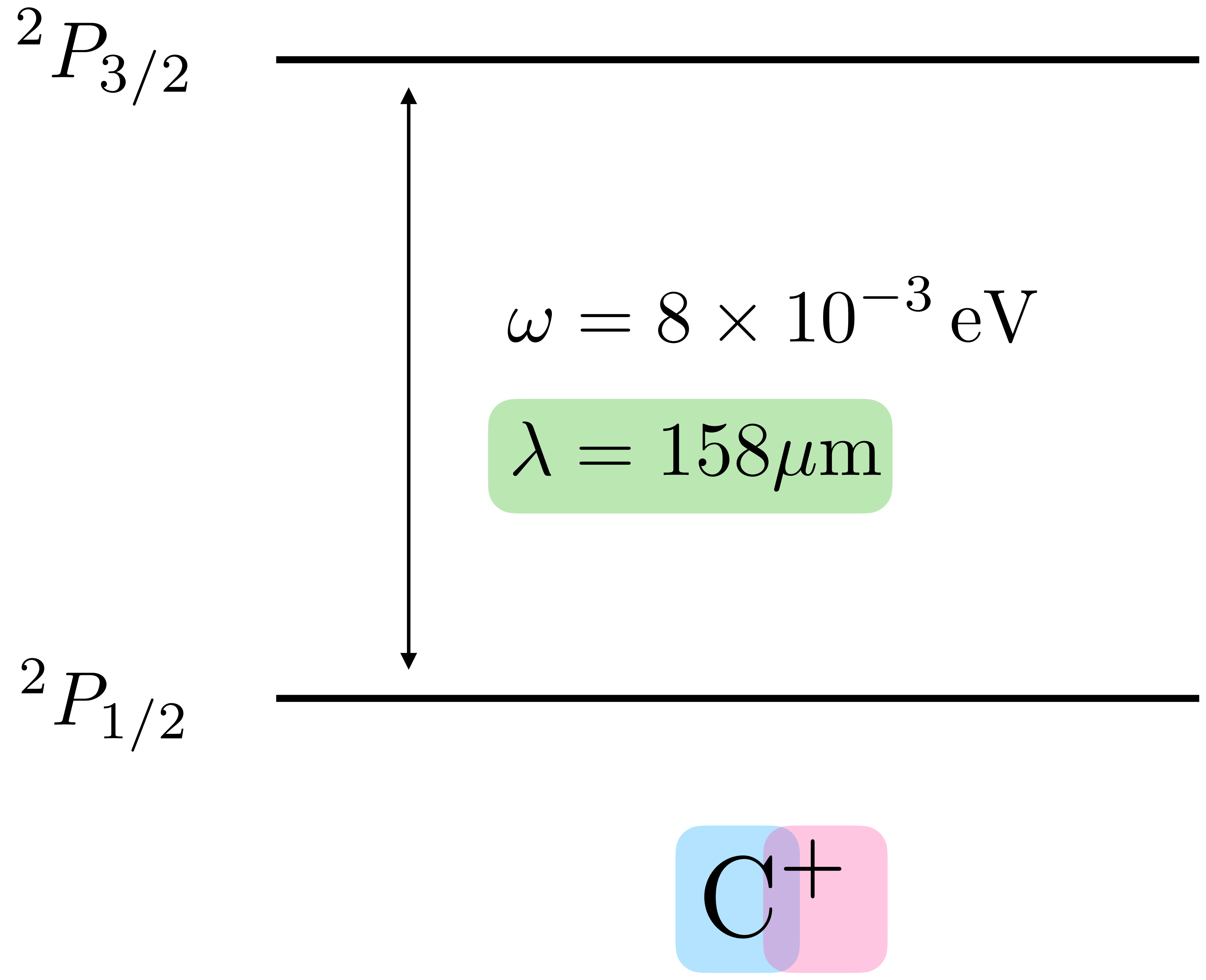
radiative decay converts internal energy to photon

For warm neutral medium

metal line emission (fine structure line emission)

is dominant cooling mechanism

Let us take an example of [C II] 158 μm



The energy loss is

$$\left(\frac{dE}{dV\,dt}\right)_{\text{loss}} = \mathcal{C} = n_1 A_{10} \omega_{10}$$

n_1 density of excited state (1/cm^3)

A_{10} spontaneous decay rate (1/sec)

ω_{10} transition frequency (eV)

$$\left(\frac{dE}{dV\,dt}\right)_{\text{loss}} = n_1 A_{10}\omega_{10}$$

radiative decay rate (A10) and frequency (w10) are well-known

$$\left(\frac{dE}{dV\,dt}\right)_{\text{loss}} = n_1 A_{10}\omega_{10}$$

the excited population can be obtained by solving

radiative decay — collisional excitation

$$\frac{dn_0}{dt} = n_1\left[A_{10} + n_c(\sigma v)_{1\to 0}\right] - n_0 n_c(\sigma v)_{0\to 1} = 0$$

collisional de-excitation

n_c : density of colliding partner

$$\left(\frac{dE}{dV\,dt}\right)_{\mathrm{loss}} = n_1 A_{10}\omega_{10}$$

the excited population can be obtained by solving

$$\frac{dn_0}{dt} = n_1\left[A_{10} + n_c(\sigma v)_{1\to 0}\right] - n_0 n_c(\sigma v)_{0\to 1} = 0$$

$$\frac{n_1}{n_0} = \frac{n_c(\sigma v)_{0\to 1}}{A_{10} + n_c(\sigma v)_{1\to 0}} \simeq \frac{n_c(\sigma v)_{0\to 1}}{A_{10}}$$

collisional excitation rate

$$\left(\frac{dE}{dV\,dt}\right)_{\rm loss} = \mathcal{C} = n_1 A_{10}\omega_{10} \approx n_0 n_c (\sigma v)_{0\to 1}\omega_{10}$$

For [C II] 158 µm

$$\left(\frac{dE}{dV\,dt}\right)_{\rm loss} \simeq n_0 n_c (\sigma v)_{0\to 1}\omega_{10} \quad \sim 8\times 10^{-16}\,{\rm eV/cm^3/sec}$$

$$\sim 10^{-27}\,{\rm erg/cm^3/sec}$$

$$\omega_{10} = 8\times 10^{-3}\,{\rm eV}$$

$$(\sigma v)_{0\to 1} \sim 10^{-9}\,{\rm cm^3/sec}$$

$$n_H \sim 1\,{\rm cm^{-3}}$$

$$n_0 \sim 10^{-4} n_H$$

For [C II] 158 μm

$$\left(\frac{dE}{dV\,dt}\right)_{\rm loss} \simeq n_0 n_c (\sigma v)_{0\to1}\omega_{10} \quad \sim 8\times10^{-16}\,{\rm eV/cm^3/sec}$$

$$\sim 10^{-27}\,{\rm erg/cm^3/sec}$$

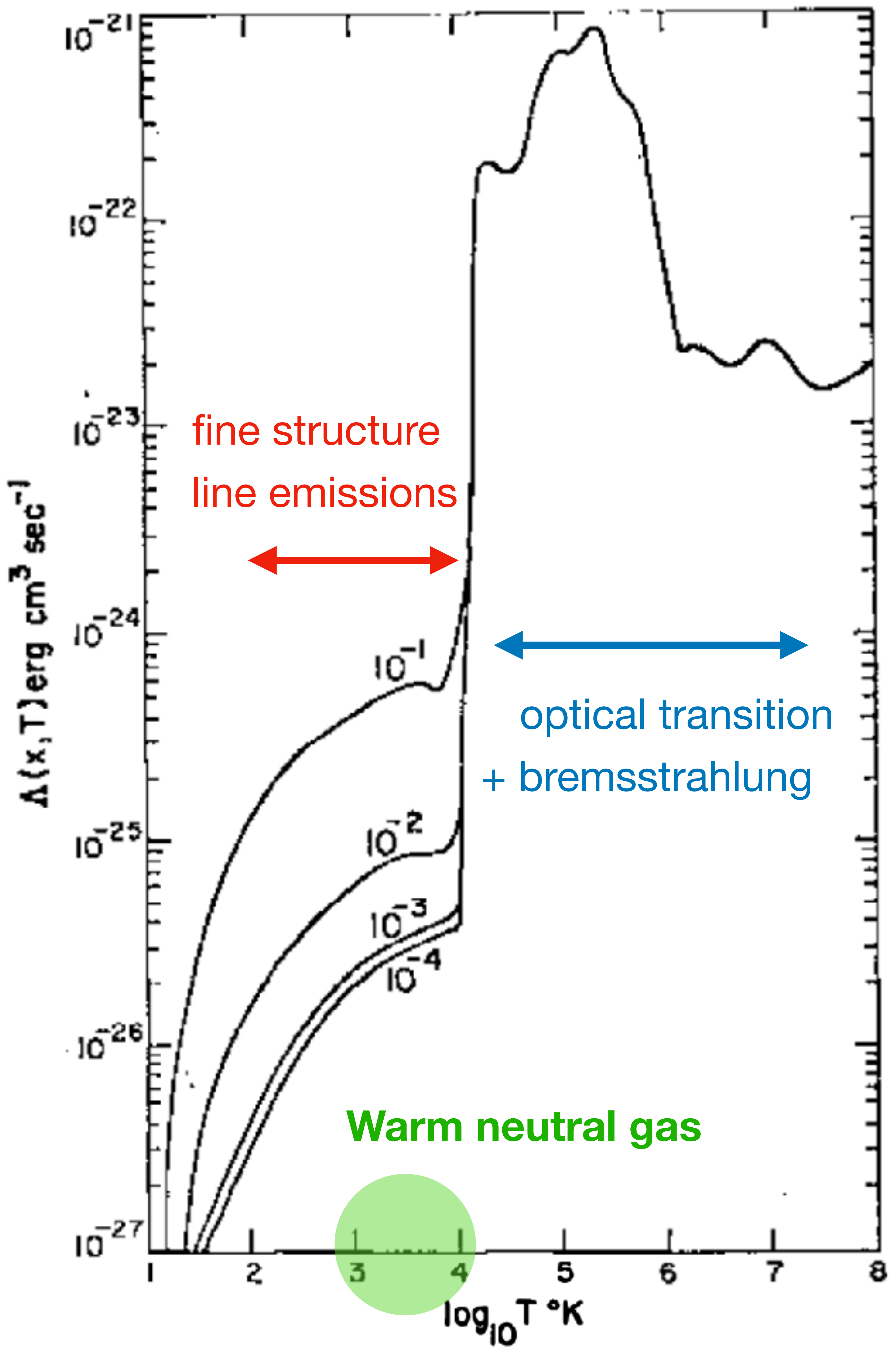
Each C+ atom loses

$$\Delta E \sim 10^{-11}\,{\rm eV}$$

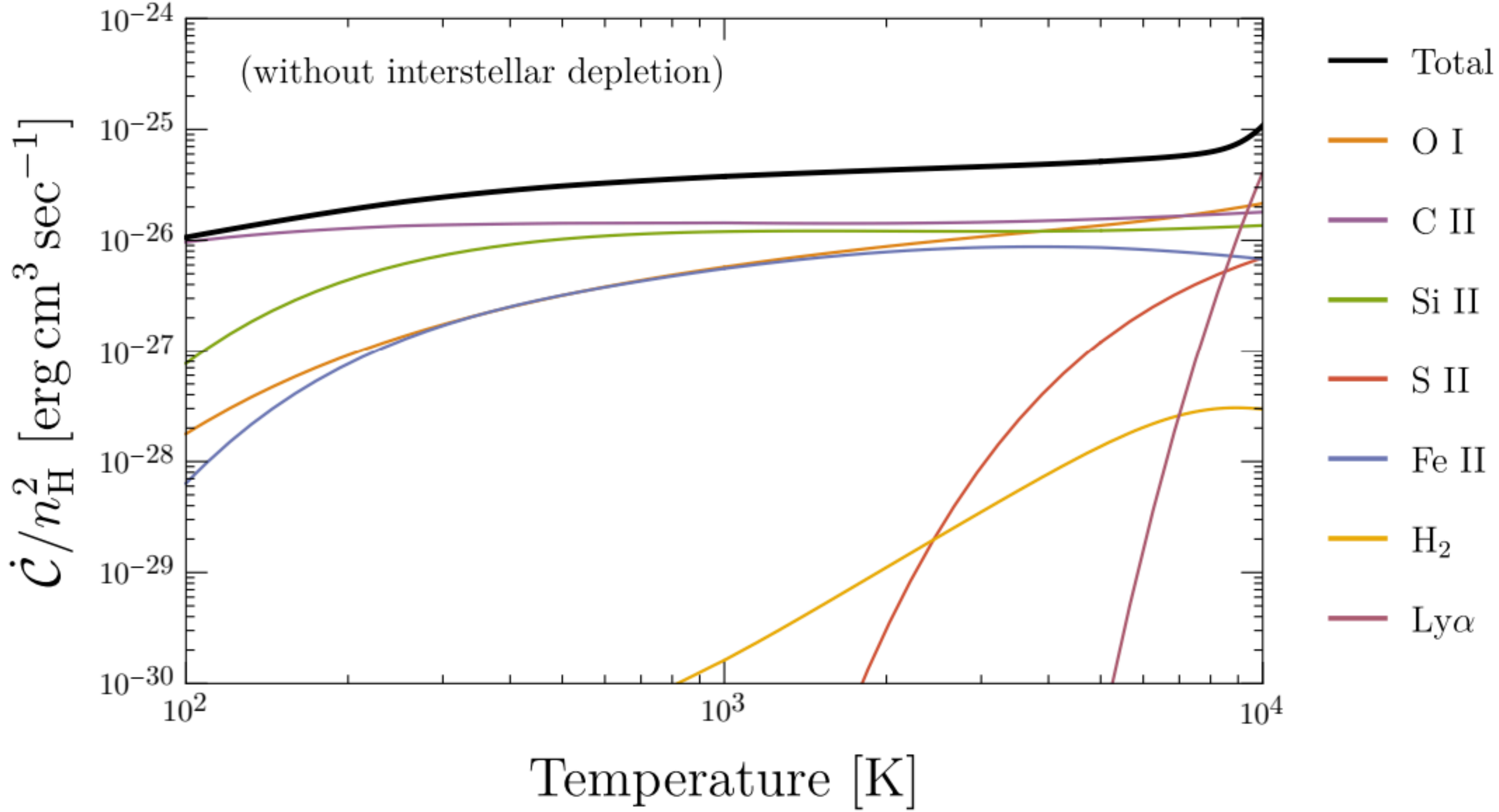
for a second due to the collision with atomic hydrogen

[C II] 158μm is one example

Including other elements …



[Dalgarno & McCray 72]



(without interstellar depletion)
$\dot{C}/n_H^2$ [erg cm^3 sec^{-1}]
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^2
10^3
10^4
Temperature [K]
Total
O I
C II
Si II
S II
Fe II
H_2
Lyα

[HK 20]

We are interested in computing the gas cooling rate

$$\frac{dE}{dtdV} = \mathcal{H} - \mathcal{C}$$

what contributes to it ?

for warm neutral medium

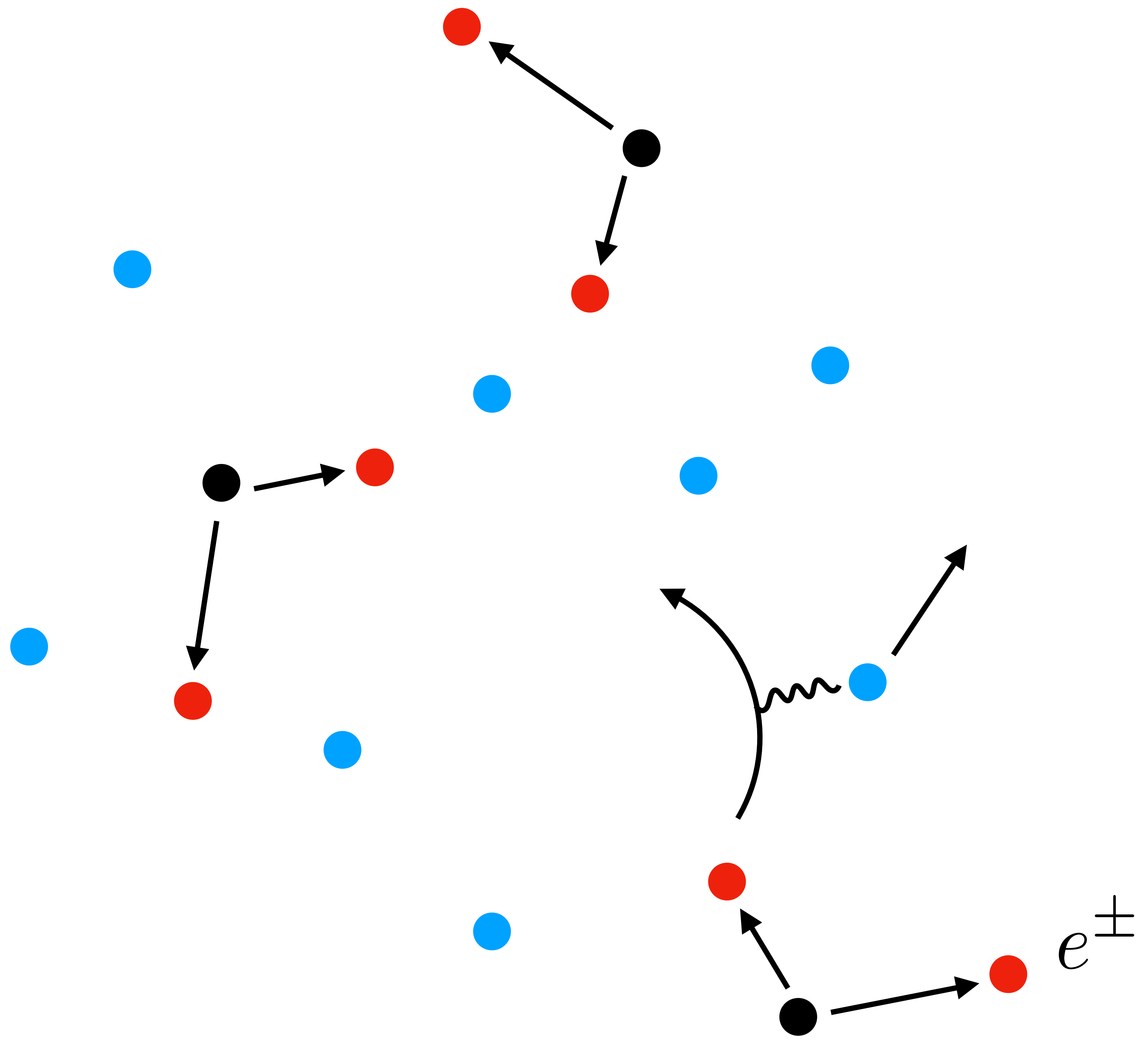
metal line emissions, mostly from C+, Si+, and O what contributes to the heating rate ?

$$\frac{dE}{dt dV} = \mathcal{H} - \mathcal{C}$$

Cosmic ray, UV photons, and many others

We will only consider PBH contribution

electrons from PBH deposit their energy as heat through Coulomb interaction



number of particles emitted per unit time

$$d\dot{N} = \frac{(\sigma v)_{\rm abs}}{e^{\omega/T} \pm 1} \frac{d^3 k}{(2\pi)^3}$$

heating rate is

a heat deposition fraction

$$\mathcal{H}_{\rm BH} = n_{\rm dm} \int d\omega (\omega - m_e) f_{\rm heat}(\omega) \frac{d\dot{N}}{d\omega}$$

kinetic energy

classical black holes can be described by a thermal system

with (approximate) black body spectrum

$$\mathcal{H}_{\rm BH} = n_{\rm dm} \int d\omega (\omega - m_e) f_{\rm heat}(\omega) \frac{d\dot{N}}{d\omega}$$

$$\sim (\rho_{\rm dm}/M_{\rm BH}) \bar{f}_{\rm heat} P_{e^\pm}$$

$$\sim 10^{-26}\, {\rm erg/cm^3/sec}$$

for 10% heat deposition efficiency and $M_{\rm BH} = 10^{-17} M_\odot$

$$\mathcal{H}_{\rm BH} = \int d\omega (\omega - m_e) f_{\rm heat}(\omega) \frac{d\dot{n}}{d\omega}$$

$$\sim 10^{-26}\,{\rm erg/cm^3/sec}$$

comparing this order-of-magnitude estimation with cooling rate

$$\mathcal{C} \simeq n_0 n_c (\sigma v)_{0\to 1}\omega_{10} \sim 10^{-27}\,{\rm erg/cm^3/sec}$$

we already see the heating from PBH would increase gas temperature

Let us apply the discussion to a specific system:

the dwarf galaxy Leo T

Leo T is

(ultrafaint) dwarf galaxy

located 420 kpc away from us

gas-rich system

hosting warm HI gas

low metallicity

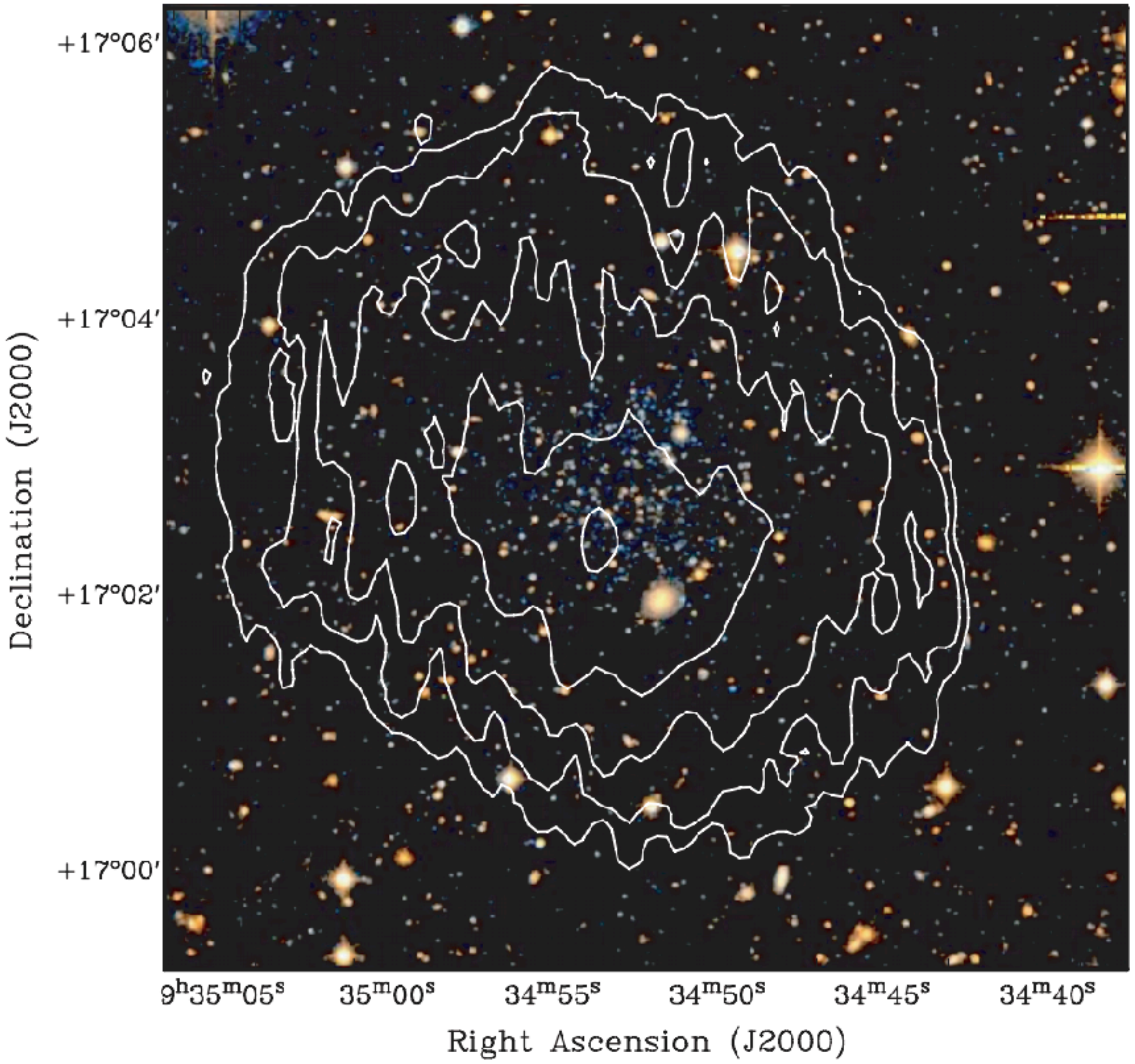
To compute the heating

$$\mathcal{H}_{\rm BH} = n_{\rm dm} \int d\omega (\omega - m_e) f_{\rm heat}(\omega) \frac{d\dot{N}}{d\omega}$$

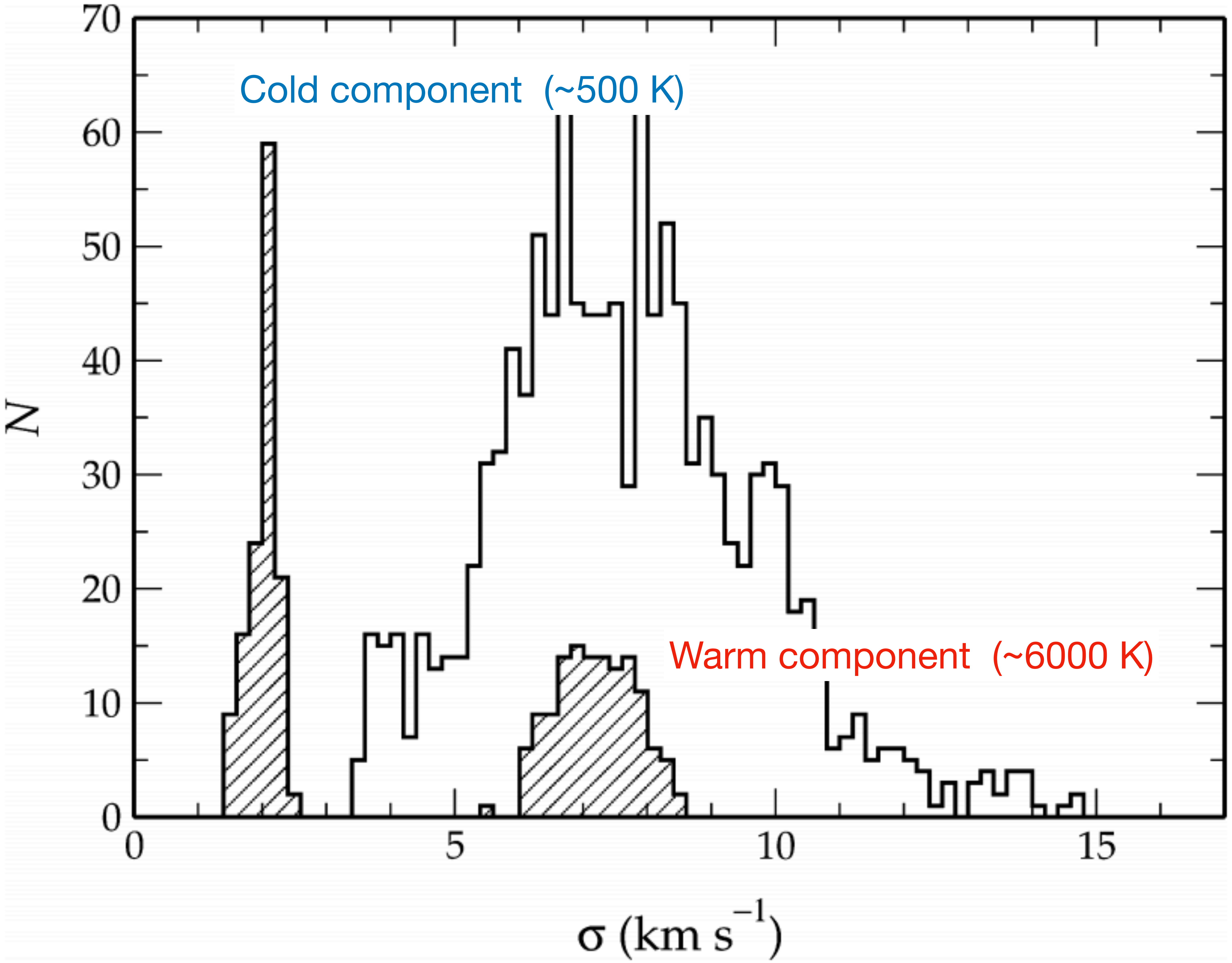
To compute the cooling

$$\mathcal{C} \simeq n_0 n_c (\sigma v)_{0\to1} \omega_{10}$$

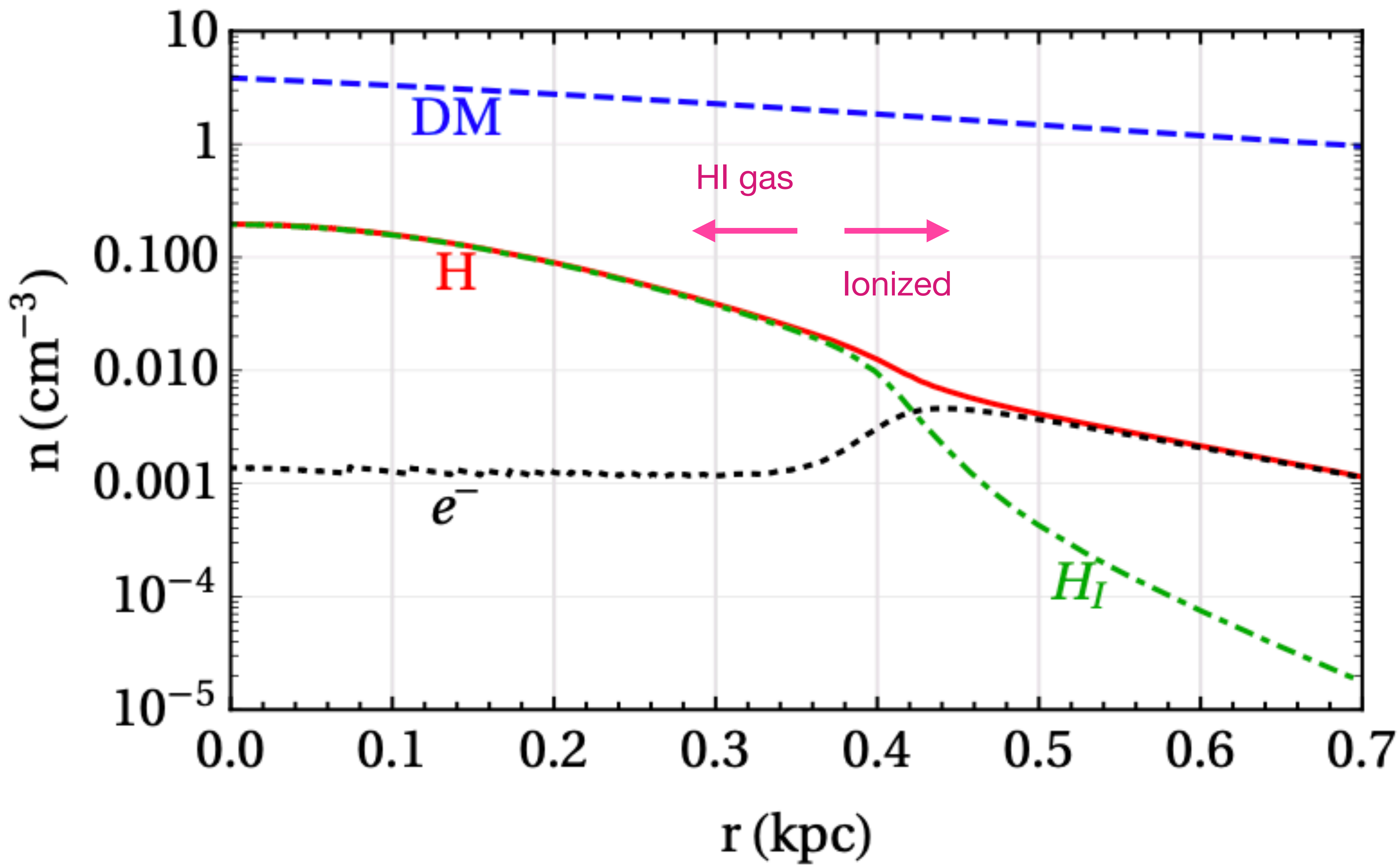
HI column density



[Ryan-Weber et al 08]



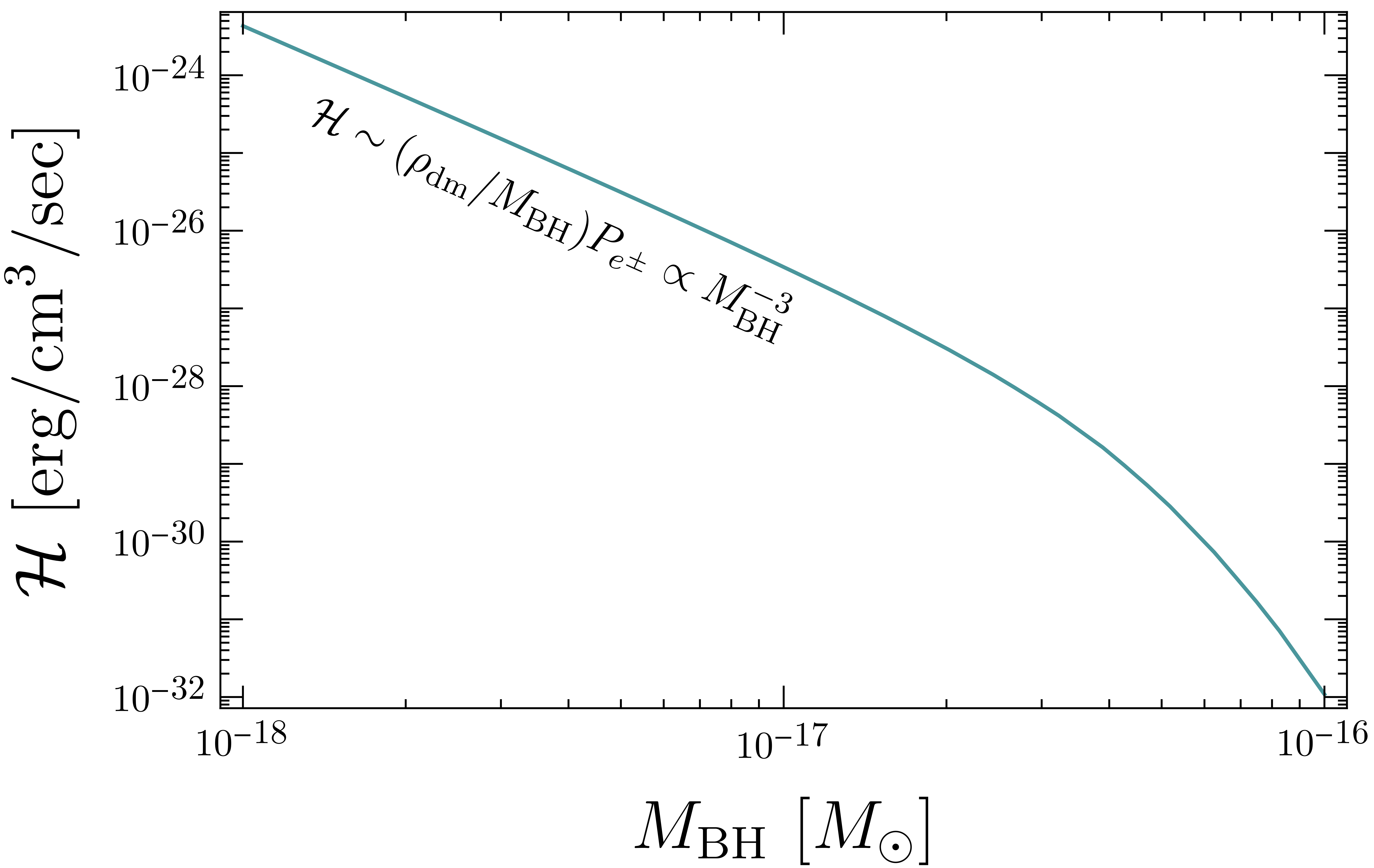
[Ryan-Weber et al 08]



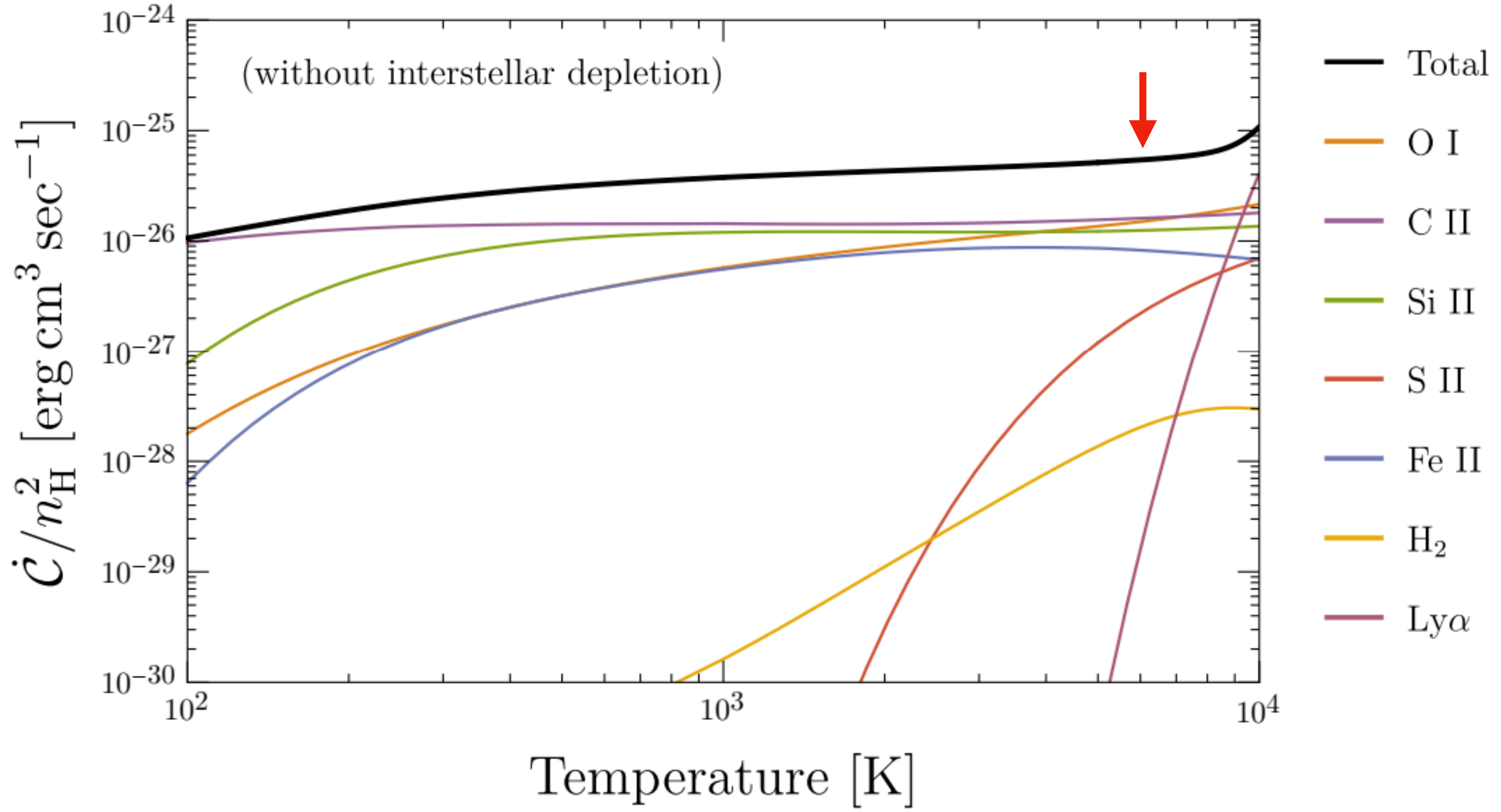
[Wadekar and Farrar 19]

[Faerman, Sternberg, and McKee 13]

Heating rate from PBHs

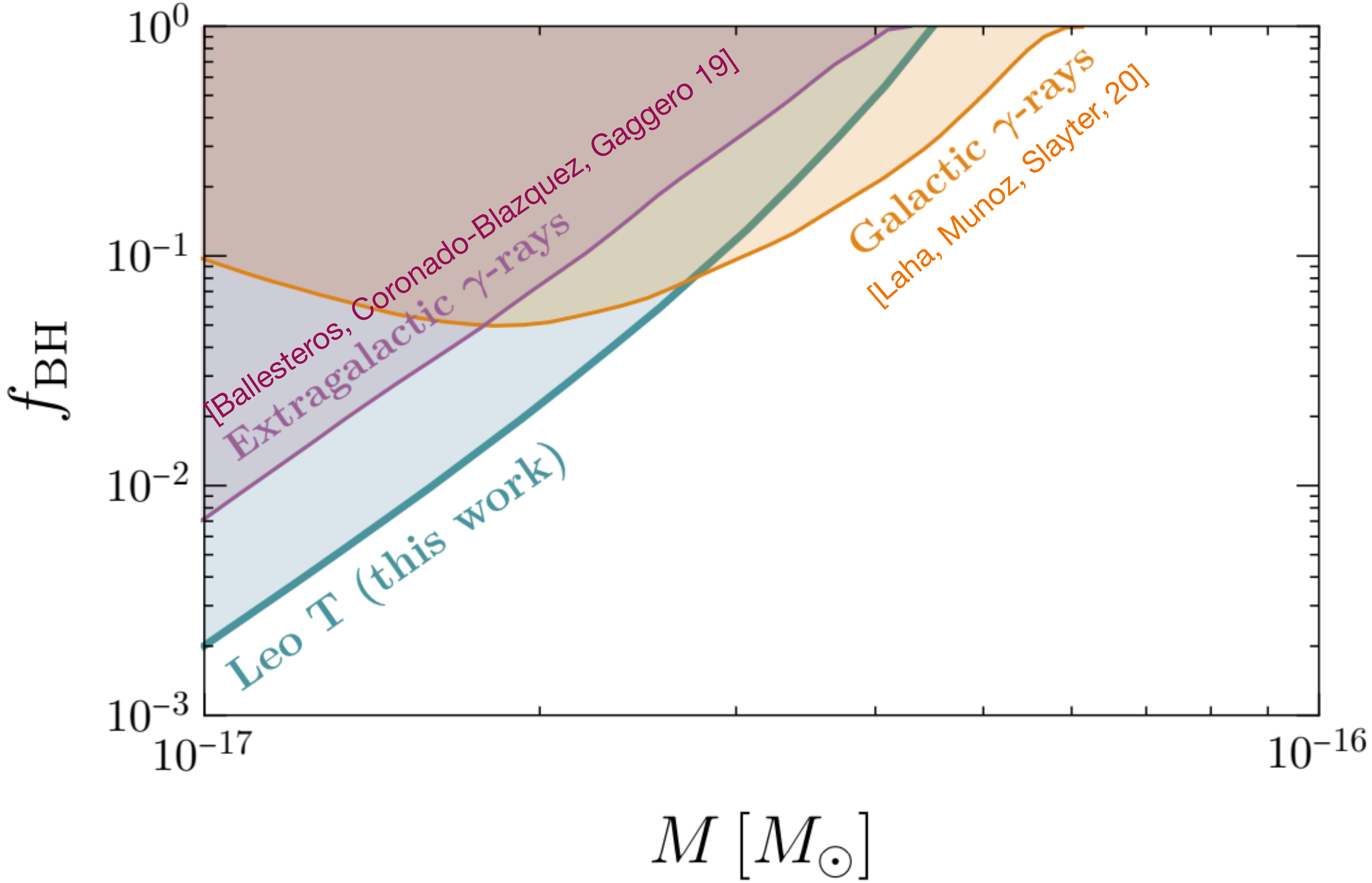


Cooling rate can be computed in a similar way



Leo T is metal poor galaxy $[\mathrm{Fe/H}] = -1.74$ [Kirby et al 13]

metal cooling rate is suppressed by $\sim 10^{[\mathrm{Fe/H}]}$



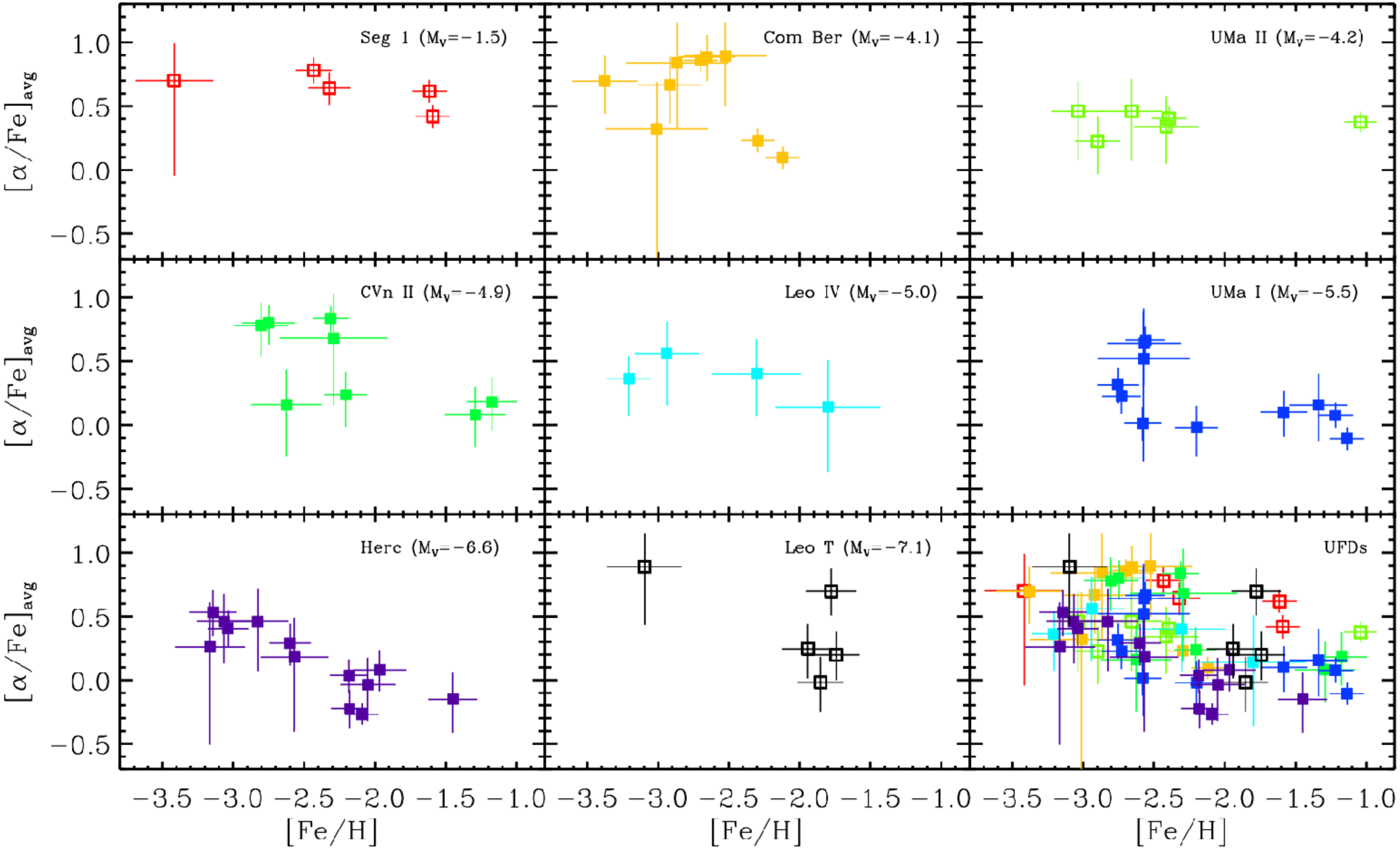
10^0
10^{-1}
10^{-2}
10^{-3}
$f_{\rm BH}$
10^{-17}
10^{-16}
$M\ [M_\odot]$
[Ballesteros, Coronado-Blazquez, Gaggero 19]
Extragalactic γ-rays
Galactic γ-rays
[Laha, Munoz, Slayter, 20]
Leo T (this work)

[HK 20]

- interstellar medium has a potential for DM searches
- Leo T hosts warm HI gas, while metal abundance is low
- this allows us to place additional constrain on PBH abundance
- other applications also exist

    DM elastic scatterings [Bhoonah et al 18, Wadekar and Farrar 19]

    Gas accretion around solar mass BH [Lu et al 20]



[Vargas et al 13]

Time scales

$$t_{\rm cool} = \frac{E_{\rm th} n}{\dot{\mathcal{C}}} \simeq 0.4\,{\rm Gyr},$$

$$t_{\rm th} = \frac{E}{(\partial E/\partial t)_{\rm el}} \simeq \frac{2}{n_e \sigma_{\rm tr} v_{\rm rel}} \sim (0.03\,{\rm Gyr}) \times \left(\frac{E}{\rm MeV}\right) \left(\frac{1.5\times10^{-3}\,{\rm cm}^{-3}}{n_e}\right),$$

$$t_{\rm ion} = \frac{E}{(\partial E/\partial t)_{\rm ion}} \sim (3\times10^{-3}\,{\rm Gyr}) \times \left(\frac{0.06\,{\rm cm}^{-3}}{n_{\rm HI}}\right) \left(\frac{E}{\rm MeV}\right),$$